# **Pressure Diagnostics of HCCI Combustion Initiated by Pulsed Flame Jet**

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## Introduction

Homogeneous Charge Compression Ignition (HCCI) engines with lean fuel/air mixtures have a number of advantages over conventional spark ignition and compression ignition engines. The onset of the HCCI combustion depends on the autoignition of the fuel, so it is quite difficult to control the ignition timing. On the other hand, Pulsed Flame Jet (PFJ) has a great potential to enhance ignition reliability and burning rate in lean Mixtures (Murase et al., 1996, 2004, Oppenheim et al., 1990, Wolanski et al., 1997,), and we have demonstrated that PFJ has a potential for controlling the start of HCCI combustion directly (Murase and Hanada, 2002, 2003). In this paper, the technique of pressure diagnostics (Oppenheim, 2004, Shen et al., 2003) was used in HCCI combustion with and without ignition timing control by PFJ.

## **Experimental Apparatus Rapid Compression Machine**

A compact rapid compression machine (RCM) as presented in Fig. 1 was used to create a high pressures and high temperatures environment (Murase and Hanada, 2002, 2003). The RCM consists of a driving air reservoir, a cam driving piston, the cam, the compression piston, and the combustion chamber. Compressed air was accumulated in the driving air reservoir. When the diaphragm between the reservoir and the driving cylinder was ruptured by a needle,



- driving piston
- Buffer air chamber
- 1 Driving air reservoir

Rapid compression machine Fig. 1



Fig. 2 Combustion chamber

Fig. 3 PFJ igniter and detail of its cavity

the driving piston was pushed to the left in Fig. 1 by the compressed air. The cam was mounted on a linear roller rail, and it was connected to the driving piston by a push rod. The compression piston was pushed upward by the rod following the cam shape, and a mixture in the combustion chamber was compressed. When the roller follower ran onto the plateau of the cam, the compression was terminated and the piston was brought to rest. The compression ratio was adjusted to 14.7. The disc-shaped combustion chamber used in the tests is shown in Fig. 2. It was a cylinder 50 mm in diameter and 28.9 mm in width, and quartz windows fitted at both ends. The PFJ igniter was located at the top of the chamber. The combustion chamber and the cylinder were wrapped in a flexible tube in which the heated oil at the designated temperature was circulated. As a result, the gas in the combustion chamber before compression was at atmospheric pressure and the designated temperature. The fuels used in the tests were n-butane/air mixtures.

#### **PFJ Igniter**

The schematic of the PFJ igniter and detail of its cavity are depicted in Fig. 3. The PFJ igniter is of the same size and shape as an ordinary spark plug, and it contains a small cavity and an orifice (Murase et al., 1996, 2004). The fuel injector is connected to the cavity via an insulator and a hollow center electrode. The latter is sealed at the end and the mixture is admitted into the cavity by two inlet ports. Rich fuel/air mixture is introduced into the cavity by the fuel injector and ignited in the cavity by spark discharge from an ordinary

	STATE		р	Т	v	е	h	w	М
			MPa	Κ	m <sup>3</sup> /kg	J/kg	J/kg	J/kg	kg/mol
PFJ	R	i	2.31	637.17	7.88E-02	1.26E+05	3.09E+05	1.82E+05	29.072
		f	5.14	779.82	4.34E-02	2.47E+05	4.70E+05	2.23E+05	29.072
	Р	(hp)i	2.31	1477.84	1.85E-01	-1.20E+05	3.09E+05	4.29E+05	28.657
		(hp)f	5.14	1601.29	9.04E-02	5.30E+03	4.70E+05	4.65E+05	28.657
w/o PFJ	R	i	3.16	664.37	6.01E-02	1.49E+05	3.39E+05	1.90E+05	29.072
		f	4.56	728.87	4.58E-02	2.03E+05	4.12E+05	2.08E+05	29.072
	Р	(hp)i	3.16	1501.19	1.38E-01	-9.67E+04	3.39E+05	4.36E+05	28.657
		(hp)f	4.56	1556.93	9.92E-02	-4.02E+04	4.12E+05	4.52E+05	28.657

Table 1 Thermodynamic properties



model and their analytic functions

automotive ignition circuit between the center electrode and the ground electrode. In the PFJ igniter, the cavity volume and the orifice diameter used were 500 mm<sup>3</sup> and 2.5 mm respectively. The fuel provided to the fuel injector here should be in a gaseous state. As the vapor pressure of n-butane is low (0.2 MPa at 293 K), methane/air mixture was used in PFJ.

## **Pressure Diagnostics**

Pressure diagnostics method (Oppenheim, 2004) carried out here consists of two steps: the dynamic stage and the exothermic stage. The dynamic stage expresses the dynamic features of combustion which is manifested by the rise in the polytropic pressure model,  $\pi(t) \equiv p(t)v_s(t)^n$ , where p,  $v_s, t, n$  denote the pressure, the volume of the cylinder-piston enclosure normalized with respect to the clearance volume, time, the polytropic index corresponding to the process of compression, respectively. Figures 4 and 5 present the measured pressure profile and the polytropic pressure model of HCCI combustion with and without ignition timing control by PFJ, respectively (the equivalence ratio of the n-butane/air  $\phi = 0.35$ , temperature before compression  $T_1 = 313$  K, ignition timing of PFJ  $t_1 = 42.5$  ms). In these figures, *life functions* are displayed by the continuous lines. The process of compression is expressed in the constant polytropic pressure model, and the initial state of the dynamic stage is expressed by the point  $\mathbf{i}$ , and its final state is expressed by the point  $\mathbf{f}$ . The exothermic stage demonstrates the exothermic feature of combustion, and then pressure diagnostics solves the inverse problem of combustion based on the balances of mass, volume, and internal energy. Thermodynamic properties of the components of the exothermic stage were listed in Table 1. In the exothermic stage, starting point and terminating point are expressed by i and t, respectively. The state diagram of reactants and products, which shows a relation between internal energy, e, and the mechanical work,  $w \equiv pv$ , is presented in Fig. 6. It demonstrates the effect of energy expenditure and its loss incurred by heat transfer to the walls. Finally, the effective use of the heat released by the reactions of fuel is summarized in Fig. 7. In Fig. 7, the mass fraction of generated products,  $y_P$ , is considered to consists of an effective part,  $y_E$ , and ineffective part that is caused by the heat losses to the walls. The



effective mass fraction achieved by PFJ was 0.37, which is 42.3% larger than that of HCCI combustion without ignition timing control by PFJ.

# Conclusion

The pressure diagnostics was carried out in HCCI combustion with and without ignition timing control by PFJ, and it was revealed that the HCCI combustion with ignition timing control by PFJ shows higher effective use of heat released by the reactions of fuel than that without ignition timing control by PFJ.

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